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Cathodic Protection of Bridges

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Abstract:	The corrosion of embedded reinforcement, caused by the presence of chloride ions in concrete, causes serious deterioration in highway structures. Cathodic protection is the only method presently available of arresting active corrosion. It consists of applying sufficient electrical current to the surface of the reinforcing steel to prevent it from discharging ions so that corrosion does not occur. The technology for the cathodic protection of steel in concrete is relatively new. Ontario is the only jurisdiction to use cathodic protection as a routine procedure, and has done so since 1978. The system, which is used on bridge decks, consists of cast iron anodes positioned in recesses on the deck and a secondary anode of electrically conductive bituminous concrete over the entire deck surface. Current is supplied to the deck anodes by a transformer-rectifier. Research studies were initiated in1981 to develop a viable method of applying cathodic protection to bridge substructure members. Eight experimental systems were installed in 1982 – 83, two larger demonstration projects in 1984, and one system in 1985. Several of the systems were found to be effective in stopping the corrosion and the work is now underway to improve the long-term durability of the components.
Key words	bridge decks, bridge structures, cathodic protection, chlorides, corrosion, reinforcing steels, substructures
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Cathodic Protection of Bridges

by D. G. Manning and H. C. Schell

INTRODUCTION

Considerable efforts have been expended in recent years to develop methods for the rehabilitation of highway bridges which have deteriorated as a result of the corrosion of embedded reinforcement. Most of this work has concentrated on bridge decks (1,2), but similar deterioration also occurs in substructure elements where it is more difficult and expensive to repair.

The Ontario Ministry of Transportation and Communications has developed a systematic approach to bridge deck rehabilitation (3,4). Three methods of rehabilitation are used: concrete overlay, cathodic protection, and application of a waterproofing membrane. While all the methods can extend the service life of a deck, only cathodic protection positively arrests the corrosion processes. This paper describes the cathodic protection system used on bridge decks in Ontario and the progress which has been made in the development of cathodic protection systems suitable for application to bridge substructure components.

CORROSION OF STEEL IN CONCRETE

Corrosion is an electrochemical process and, for an electrochemical cell to function, four basic elements are necessary: an anode, where corrosion takes place; a cathode, which does not corrode but maintains the ionic balance of the corrosion reactions; an electrolyte, which is a solution capable of conducting electric current by ionic flow; and a conductor which connects the anode and cathode. In the case of steel in concrete, the anodes and cathodes occur on the reinforcing steel, which also acts as the conductor; moist concrete acts as the electrolyte. This is illustrated schematically in Figure 1.

Steel in concrete is normally protected by the highly alkaline cement paste. However, chloride ions (which may be present in the mix ingredients, or may penetrate hardened concrete exposed to a marine environment or deicing salts) or carbonation of the concrete can destroy the concrete's ability to maintain the steel in a passive state. If moisture and oxygen are present, corrosion can occur.

As the steel corrodes, the corrosion products (rust) occupy more volume than the parent iron, thereby exerting stresses on the concrete. This results in cracking of the concrete. The cracking often causes a fracture plane or delamination at or near the level of the reinforcement. As the corrosion processes continue, delaminated concrete eventually becomes detached from the concrete member, resulting in a spall.

PRINCIPLES OF CATHODIC PROTECTION

The theory of cathodic protection is to apply sufficient direct current to the surface of the reinforcing steel to prevent it from discharging ions so that corrosion does not occur. The steel then becomes cathodic with respect to an external anode; hence the term cathodic protection.

Cathodic protection has been widely used to prevent corrosion in such applications as pipelines, chemical plants, oil refineries and underground storage tanks. However, its application to reinforced concrete structures is relatively new. While the principles of cathodic protection are common to all applications, reinforced concrete presents three particular problems:

i) Concrete has a high resistivity.
ii) Concrete is attacked by acid which may be generated at the anode.
iii) The potential of the steel must be maintained within a narrow range. If it is too low, corrosion can occur; if it is too high, deterioration of the concrete around the reinforcing steel may take place.

The key to the successful cathodic protection of steel in concrete is to provide uniform current density to the reinforcement, thereby maintaining an even potential distribution. The resistance between the anodes and all the reinforcement must be kept uniformly low and the anodes should be as large as possible to minimize the applied current density.

Two methods of applying the current to the concrete are through the use of galvanic anodes or an impressed current source. The source of impressed current may be a battery or a rectifier which converts AC line power to DC. In the galvanic anode system, a metal higher in the electromotive series than iron must be used. Most investigations have used zinc anodes. The limiting factor of sacrificial anode systems is their low driving voltage. Although studies have indicated that galvanic cathodic protection systems are possible (5,6), their effectiveness on highway structures is questionable. Consequently, except for research investigations, only impressed current systems have been used in Ontario.

CATHODIC PROTECTION OF BRIDGE DECKS

History

The first installation of cathodic protection to a bridge deck was by the California Department of Transportation in 1973. The system consisted of high-silicon cast iron primary anodes and a secondary anode consisting of a mixture of asphalt and metallurgical coke breeze covered by a conventional wearing course. A similar system was installed by the Ontario Ministry of Transportation and Communications on three bridges in 1974 and one other in 1975.

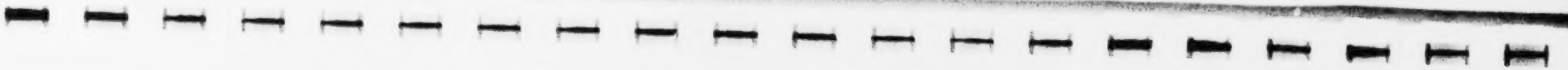
Following this experience, Ontario introduced two significant developments in 1976:

- All the hardware and wiring was embedded in the deck surface so that the bituminous surfacing can be removed and replaced, if necessary, without replacing the other cathodic protection components.

- The composition of the secondary anode was modified to produce a mixture having physical characteristics similar to conventional bituminous concrete. This was done by adding sand and stone to the coke-asphalt mixture to decrease the voids content and increase the stability. This also resulted in an increase in resistivity, though the increase was considered acceptable. A comparison of typical proportions and properties of the coke-asphalt mixture used in California and the conductive concrete developed in Ontario is given in Table 1.

These developments were incorporated in all subsequent installations in Ontario. The application of cathodic protection became one of the three operational procedures for the rehabilitation of bridge decks in 1978. Ontario remains the only jurisdiction in North America to use cathodic protection routinely as opposed to research and demonstration installations. By the end of 1985 there were 31 installations on Ministry owned bridges (listed in Table 2). This represents a substantial proportion of all the cathodic protection systems installed on bridges in North America.

In recent years, different materials have been used as anodes in other jurisdictions. Many of these utilize the same materials discussed in this paper, for application to bridge substructure components. However, they have not been applied to bridge decks in Ontario because the present system is inexpensive and is performing effectively. Typical installation costs are in the range of $40 to $60 per square meter of deck surface (excluding the costs of concrete repairs). Furthermore the secondary anode satisfies the objectives of minimizing circuit resistance, ensuring uniform current distributicn, and providing maximum



contact area between the anode and the concrete to minimize attack due to the dissipation of gases or acids at this interface. Many of the alternative systems utilize anodes which result in a much smaller contact area and therefore, the desirable features of the secondary anode are compromised.

Ontario's Bridge Deck Cathodic Protection System

The first step in the application of cathodic protection to bridge decks is to expose the deck surface (if it has a bituminous surfacing) and repair any spalled or delaminated areas to their original condition using conventional concrete repair techniques.

A schematic representation of the cathodic protection system used by the Ministry is shown in Figure 2. The essential components of the cathodic protection system are:

i) A dc power supply (rectifier).
ii) Current distribution system (anodes).
iii) Electrical connections to protected metal (rebar grounds).
iv) Evaluation and control devices (probes, reference cells, controllers).

A typical placement of the components on a bridge between 10 and 20 m wide is shown in Figure 3. Current flows from the rectifier to the anodes and through the concrete to the reinforcing steel. A connection between the reinforcing steel and the rectifier completes the circuit.

The primary anodes are disc-shaped cast iron anodes which are embedded in the deck surface. One anode is provided for each 50 to 75 m^2 of deck area. The anodes are placed in lines with normally not more than 15 m between lines. A 40 mm thick layer of electrically conductive asphalt is placed over the entire deck surface and acts as a secondary anode. The conductive layer is covered with a 40 mm thick wearing surface of conventional asphalt, to protect the anode and provide a durable skid resistant driving surface.

Several connections are made to the reinforcing steel. This is done to ensure that areas of the deck are not electrically isolated and to prevent any significant voltage drop along the length of the structure. In practice, all the reinforcing steel in bridge decks tested to date, has been found to be electrically continuous.

Zinc-zinc sulphate half-cells are used to control the rectifier to maintain the polarized potential of the steel within the acceptable range of -0.85V to -1.10V CSE. Although only one half-cell is used to control the rectifier at any one time, the half-cells are prone to failure and hence a minimum of three are placed in each deck.

Graphite probes are placed at several locations in the concrete deck surface to sense the applied and polarized potentials of the secondary anode layer. They are used to examine the uniformity of current distribution over the entire deck surface. If the zinc-zinc sulphate half-cells become unreliable, a graphite probe can be used to control the rectifier.

All the hardware is recessed in the deck. The wiring is placed in slots cut in the deck surface and run to the curb where it is bundled and cast in a concrete fillet strip. At a convenient location, the wires pass through a hole in the deck into plastic conduit to the control panel and rectifier. Standard details and the methods of construction are given in Part Two of the Ministry's Bridge Deck Rehabilitation Manual (3).

All the wiring from the deck is terminated at a control panel, where readings to monitor the performance of the installation can be made. The control panel is usually located on the side of an abutment to avoid damage from runoff through the expansion joint. The rectifier is positioned adjacent to the control panel. Current requirements for adequate protection against corrosion have been found to be in the range of 5 to 15 mA/m^2 of concrete surface with a rectifier voltage output of less than 5V on a typical structure.

The performance of the cathodically protected decks has been good. The conductive layer applied to one-half of a structure in 1974 was removed in 1977. The cathodic protection was found to have prevented deterioration, while the unprotected half of the deck continued to delaminate (7). Cathodic protection was then applied to the entire deck surface. Concern has been expressed in some other jurisdictions for the ability of the conductive layer and wearing course to perform under conditions of heavy traffic loading. However, no failures of either the conductive mix or the wearing course have been experienced. One group of four structures which were cathodically protected in 1979 are located on a section of freeway having an AADT of 220,000. After six years the bituminous concretes have shown no deterioration.

Monitoring of all of the deck systems continues. Based on detailed examination of three structures under cathodic protection since the mid-seventies, it appears that the current necessary to maintain typical "protected" potential levels on the steel decreases with time. This examination included removal of small areas of the asphalt layers to expose the concrete surface, allowing half-cell potentials to be measured with a portable cell. The condition of the coke asphalt layer was found to be excellent on all three bridges.

CATHODIC PROTECTION OF BRIDGE SUBSTRUCTURES

Although the principles are unchanged, the materials and methods of installing cathodic protection on bridge decks cannot be used

on bridge substructure components. In view of the successful experiences on decks, the Ministry initiated a research program in 1981 to develop a cathodic protection system suitable for application to bridge substructures. The program involved a number of laboratory and exposure plot studies of the components of cathodic protection systems, but the major activity has been the installation of eleven experimental systems on in-service structures. Eight of these systems were installed at the Burlington Bay Skyway Test Site; Systems 1 to 4 were installed in 1982, with Systems 5 to 8 being added in 1983 (8,9,10). Two systems were installed at the Leslie Street Bridge Test Site in 1984, and another in 1985.

The Burlington Bay Skyway Test Site

The Burlington Bay Skyway Bridge is a multiple span, high level structure over the entrance to Hamilton Harbour in Southern Ontario. It was selected as a test site because corrosion was occurring in the columns as a result of exposure to surface runoff, containing deicing salts, from the deck through open expansion joints.

A summary of the main features of the eight systems at the site is given in Table 3. With the exception of System 4, all the installations were impressed current systems.

Systems 1 to 4 were installed three panels high on the south column face and two panels high on the remaining faces. A "panel" refers to the area on one face between adjacent rustication strips. The rustication strips are visible in Figure 4. This configuration was chosen to determine if protection of the third panel on the south face influenced corrosion activity on the adjacent, unprotected faces. Since it did not, Systems 5 to 8 were installed three panels high on all faces.

Although several materials and configurations were used, it is convenient to generalize the description of the eight systems as follows:

- System 1 consisted of conductive polymer primary anodes.
- System 2,6, and 8 were different conductive paints.
- Systems 3 and 7 utilized a carbon fiber secondary anode.
- System 4 was the single galvanic system.
- System 5 consisted of a proprietary long-line polymer anode.

A 40 mm thick shotcrete layer was applied to Systems 1,3,4,5, and 7. Figure 4 shows Systems 1,2, and 3 under construction. Systems 5,6, and 7 are shown in Figures 5, 6, and 7 respectively.

Instrumentation -- One of the major difficulties in conducting an evaluation of several alternative cathodic protection systems is to obtain a measure of their effectiveness within a relatively short period of time. The magnitude of this difficulty is increased because of the lack of suitable instrumentation available commercially. Consequently, instrumentation had to be designed and fabricated. Macrocells, current distribution probes, and electrical resistance probes were installed in Systems 1 to 4.

The macrocell is a strong natural corrosion cell, installed in the structure, in which current flow can be measured. The ability of the cathodic protection to reverse the direction of current flow in the cell (i.e. stop corrosion) is one indication of the effectiveness of the protection. A zinc-zinc sulphate reference cell and a thermocouple were embedded adjacent to each macrocell. The current pick-up probes consisted of short pieces of rebar embedded at the level of the reinforcing steel at various points in the structure. They were used to measure current density and uniformity throughout the system. The current distribution probes consisted of three current pick-up probes installed at the same location but at different depths (100 mm, 180 mm, and 250 mm) from the concrete surface. They were used to measure the variation of current density with depth. The electrical resistance probes were designed to give a quantitative measurement of corrosion in terms of metal loss per year.

The instrumentation used in Systems 5 to 8 was modified following one year's experience in monitoring Systems 1 to 4. The changes were as follows:

1. The electrical resistance probes did not function satisfactorily in Systems 1 to 4 and were not used.

2. The current distribution probes in Systems 1 to 4 gave very consistent data. It was decided there was no value in repeating the measurements in Systems 5 to 8.

3. Fewer macrocells were constructed in order to reduce installation costs.

4. In addition to the zinc-zinc sulphate reference cells, molybdenum-molybdenum oxide, silver-silver chloride, lead, and carbon cells were installed in System 5. Silver-silver chloride and molybdenum-molybdenum oxide cells were also installed in System 6 and Systems 7 and 8 respectively. In all cases, the additional reference cells were installed adjacent to the reinforcing steel, but not adjacent to the macrocells. The number and location of the various types of instrumentation for a typical system are shown in Figure 8.

Operation -- Systems 1 to 4 were activated in October 1982. E-log I polarization tests were conducted (9) and the three impressed current systems were set to a constant current of 500 mA corresponding to an average current density of 13 mA/m^2 of concrete surface. The sacrificial anode system was activated by connecting the anodes to the column reinforcing steel and had an initial driving voltage of approximately 300 mV. Systems 5 to 8 were powered in November 1983 to maintain the same average current density on the concrete surface as applied in Systems 1 to 3. This current level has been maintained throughout the monitoring period, except when circuit resistance increased so that the maximum output of the rectifier was insufficient or when the systems were intentionally switched off to observe depolarization characteristics.

Results of Monitoring Program -- One requirement for the satisfactory performance of a cathodic protection system is that the protection current be maintained at an acceptable voltage level. Typical operating voltages for all eight systems are shown in Figure 9. Where the voltage levels during summer and winter differed significantly, average voltages for each period are shown in Figure 9. Voltage levels were found to vary in response to changes in temperature and humidity. Those systems with shotcrete overcoats exhibited the least fluctuation in voltage. Slightly higher voltages were generally recorded in the winter months, corresponding to increases in anode-to-reinforcing steel resistance. However, System 2 exhibited large increases in driving voltage in the summer months as a result of poor contact between the primary anodes and the paint, and drying of the concrete surface below the paint. The other paint systems, 6 and 8, showed little change in voltage requirements during periods of hot, dry weather.

The initial application of cathodic protection current was sufficient in all the impressed current systems to reverse current flow in the macrocell probes. That is, under cathodic protection, the corroding anode of the macrocell probe became a current-receiving cathode. The macrocell probes located outside the protected area to serve as controls, remained anodic through the monitoring period. In contrast, probes within protected areas were cathodic during periods when current was applied but shifted in the anodic direction when the power was switched off. There was a tendency for this anodic shift to decrease over time, as systems were periodically switched on and off. For this reason, it would appear that macrocell probes are most effective as monitoring tools during the early stages of system operation.

The current density of 13 mA/m^2 applied to the concrete surface corresponded to an average of approximately 2.8 $\mu A/cm^2$ on the surface of the reinforcing steel. Current densities in all the impressed current systems on probes embedded at the level of the first layer of reinforcement were typically in the range of 2 to 6 $\mu A/cm^2$ during periods when power was applied. During "off"

periods, current flow to or from the current pick-up probes was essentially zero. The pick-up probes were also found useful in measuring the uniformity of current flow, since uniformity is an important requirement for a successful system. They could be used to investigate the effects of varying anode spacing to optimize the design of each system.

The current distribution probes installed in Systems 1,2, and 3 were designed to measure the variation of current density with depth as compared with the pick-up probes which were used to measure the uniformity of current over the concrete surface. The average results for the three systems for the period October 1982-April 1983 indicate that probes at the 250 mm depth received about one-fifth of the current received by those at the 100 mm depth. The results showed that even though the deepest probes were embedded at a greater depth than the two layers of reinforcement in the column, they received some beneficial effects from cathodic protection.

Reference cell potentials were measured and the polarization shift between instant-off and static potentials was compared with the value of -100 mV, which is one of a number of criteria suggested for protection against corrosion (11). This criterion was satisfied by all the impressed current systems until connections failed in Systems 1,2, and 3 and degradation of the paint occurred in System 8. The different types of reference cells exhibited a wide range of behaviour. The zinc-zinc sulphate cells were erratic, while the molybdenum and silver-silver chloride cells became unstable during periods of low temperature. The graphite and lead cells appeared relatively stable, but too few were used to draw conclusions. The absence of a reliable reference cell suitable for use in reinforced concrete is one of the major difficulties in monitoring cathodic protection installations.

The output of the galvanic system, System 4, fluctuated on both a seasonal and day-to-day basis. The voltage, as shown in Figure 9, was very low. Current output was insufficient to maintain reference cell polarization shifts of -100 mV and none of the macrocells were consistently reversed. Galvanic systems of this type using zinc do not appear to provide adequate protection against corrosion.

Although all the impressed current systems initially functioned satisfactorily from the standpoint of cathodically protecting the steel, some components deteriorated in service. The connections between the lead wires and the anodes in Systems 1 and 3 corroded.

This experience indicates the need for carefully designed and well insulated connections. It may be desirable to keep the connections outside the concrete, where possible, or embed them within the anode (as was done for the primary anodes in Systems 6 and 7). The shotcrete in Systems 1,3,5, and 7 delaminated

from the columns. The delamination of the shotcrete is of considerable concern and the reasons for the delamination are not fully understood. The premature failure of the shotcrete, together with its relatively high cost and undesirable appearance, suggest that it would be preferable to utilize systems which do not include a shotcrete overcoat even though it does minimize performance variations due to fluctuations in temperature and humidity. The paint in Systems 2 (shown in Figure 10) and 8 deteriorated during the winter months though the paint in System 6 has performed well to date.

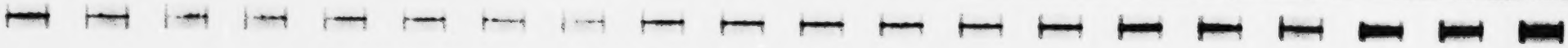
The design, construction, and monitoring of the eight systems at the Burlington Bay Test Site lead to several observations:

- It is possible to arrest corrosion in bridge substructure components through the application of impressed cathodic protection systems.
- There is insufficient current output from a galvanic system using zinc to provide adequate protection under most conditions.
- It is preferable not to use systems which include shotcrete until there is assurance that delamination will not occur.
- Long term durability of both the materials and construction details is the biggest obstacle to be overcome.

The Leslie Street Bridge Test Site

The results of the research studies at the Burlington Bay Skyway Test Site were used in the selection of two systems installed at the Leslie Street Bridge Test Site in the fall of 1984. The substructure components at this test site are spirally reinforced concrete columns with a cap beam and are much more typical of bridges in Ontario than the massive columns of the Burlington Bay Skyway.

One of the systems installed was the same as System 6 in the previous study. The other was a flame-sprayed zinc system which had been developed in California (12) while the Burlington study was in progress. The process consists of applying molten zinc to the entire surface of the concrete as illustrated in Figure 11. Current is supplied to the zinc anode at several locations on the concrete surface so that the zinc acts as the primary anode in an impressed current system, rather than as a galvanic anode. The experience gained in the Burlington study was used to reduce the amount of instrumentation necessary and to install it in such a way as to investigate several unresolved problems. Carbon, zinc, silver, and lead reference cells, as well as probes for investigating the distribution of current around a bar, were installed.



The construction of the two systems proceeded smoothly, although application of the 0.02 mm thick layer of zinc was a relatively slow process. Difficulty was encountered in applying power to the zinc system. Although care was taken to identify all the exposed steel (which was then insulated by epoxy or removed), the circuit resistance was very low, indicating that the reinforcing steel was in near contact with the surface anode. The areas of the system containing these "near shorts" (typically tie wires near the surface or localized areas of very shallow cover) were eventually isolated and the system activated. The experience indicated the advisability of spraying the entire component with a thin coat of relatively high resistance material (e.g. portland cement mortar) before applying the surface anode.

After being powered for approximately one year at a current density and voltage similar to those of the previously installed impressed current systems, the flame-sprayed zinc system continues to perform effectively. Some visible oxidation of the zinc has occurred in those areas subject to heavy runoff from the deck above, giving the surface a mottled, though acceptable, appearance. A spraying system allowing higher delivery rates of zinc to the concrete surface, thus speeding the installation process, is presently under investigation in the U.S. After several months of operation, investigation showed that approximately 20% of the paint surface had become debonded from the underlying concrete. Although the system continued to operate, higher system voltages were required, and the appearance was unacceptable. This deterioration was surprising in view of the excellent performance of this material at the Burlington Test Site. The cause is under investigation and the possible effects of localized high current densities, and adverse moisture conditions in the concrete, are being considered. No apparent deficiencies in the material, which would explain the deterioration, have been identified.

In 1985 a small scale experimental system, employing two materials new to the marketplace, was installed on two columns at the Leslie St. Site. A thin mesh anode, of precious metal and metal oxides, was installed beneath a 5 mm sprayed overcoat of a commercial cementitious coating material as shown in Figure 12. The redundancy of current paths in the anode and the ease of handling, make it attractive. The overcoat material used has been seen to perform well in laboratory studies in the U.S. and is being considered as a promising alternative to the use of shotcrete. This system has not been installed for a sufficient period of time to yield meaningful performance data.

CONCLUSIONS

1. The application of cathodic protection to bridge decks is a routine operational procedure.

2. Substantial progress has been made in developing a cathodic protection system suitable for use on bridge substructure components. The technique is feasible, but the long-term durability of the components is the biggest obstacle to be overcome.

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TABLE 1: Typical Proportions and Properties of Conductive Ashphalt Mixtures

	1973 California Coke-Asphalt Mixture	Post 1976 Ontario Conductive Concrete
Coke, % wt.	80	39
Asphalt, 85/100, % wt.	20	13.4
Stone , % wt.		34.6
Sand , % wt.		13
Air Voids , % vol.	17.8	5.0
Marshall Stability	485	1080
Marshall Flow	15.0	14.0
Resistivity, ohm cm	1.4	3.0
Density, compacted, g cm^{-3}	1.23	1.73

TABLE 2: Cathodically Protected Bridge Decks in Ontario, 1974-85

SITE NO.	BRIDGE	HIGHWAY	YEAR INSTALLED
22-092	Duffins Creek	7	1974 Re-applied 1977
19-064	Medway Creek	7	1974
37-323	Bridge No. 9	DVP/401	1974
42-067	Paint Lake	117	1975
33-141(A)	Grand River (2 bridges)	401	1976
29-092	Madawaska River	515	1978
31-085	South Nation River	31	1978
06-257	Gracie Sideroad U.P.	401	1978
34-129	PCR and CNR O.H.	QEW	1979
37-188	Humber River (4 bridges)	401	1979
18-176	Victoria Avenue U.P.	QEW	1980
01-024	Grand River	2	1980
37-186	CNR O.H. (2 bridges)	401	1981
37-341	Yonge Street O.P.	401	1982
42-141(A)	Gull River (2 bridges)	11	1982
30-074	Atherly Narrows	12	1982
31-201	County Road No. 1 U.P.	401	1983
03-043	Clyde Avenue O.P.	17	1984
03-044	Carling Avenue E.B. O.P.	17	1984
03-045	Kirkwood Avenue O.P.	17	1984
03-046	Carling Avenue W.B. O.P.	17	1984
03-048	Island Park Drive O.P.	17	1984
OS-329	North Otter Creek	9	1984
18-197	St. David's Road O.P.	58	1984
12-171	Maitland River Bridge	21	1985

TABLE 3: Summary of Important Features of Systems 1-8

System No.	Primary Anode	Secondary Anode	Overcoat	Area m^2	Type [1]
1	conductive polymer [2]	none	shotcrete	38	I
2	conductive polymer [3]	conductive paint [5]	none	38	I
3	conductive polymer	PAN carbon fiber (S & W faces), pitch carbon fiber (N & E faces)	shotcrete	38	I
4	zinc ribbon	none	shotcrete	38	G
5	conductive polymer mesh [4]	none	shotcrete	45	I
6	conductive polymer (N & W faces) graphite (S & E faces)	conductive paint [5]	latex paint (E & W faces none (N & S faces)	47	I
7	conductive polymer precast (S & E faces), in-situ (N & W faces)	PAN carbon fiber mesh (E,S & W faces), PAN carbon fiber woven with fiber-glass (N face)	shotcrete	47	I
8	platinized wire embedded in conductive paste	conductive paint [5]	none (S face) latex paint (E & W faces) latex paint + tie coat (N face)	33	I

(1) I - impressed current, G - galvanic
(2) carbon fiber core
(3) platinized niobium copper wire core
(4) copper wire core
(5) The three conductive paints had different compositions

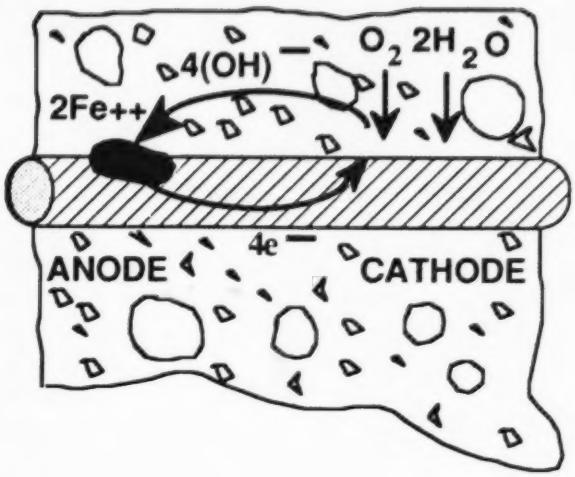


Figure 1/ Simplified Model of the Corrosion of Steel in Concrete

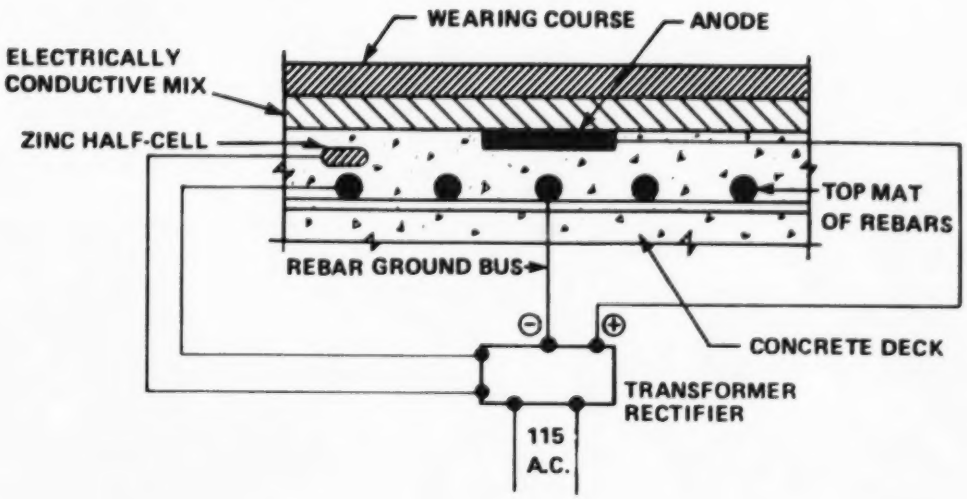
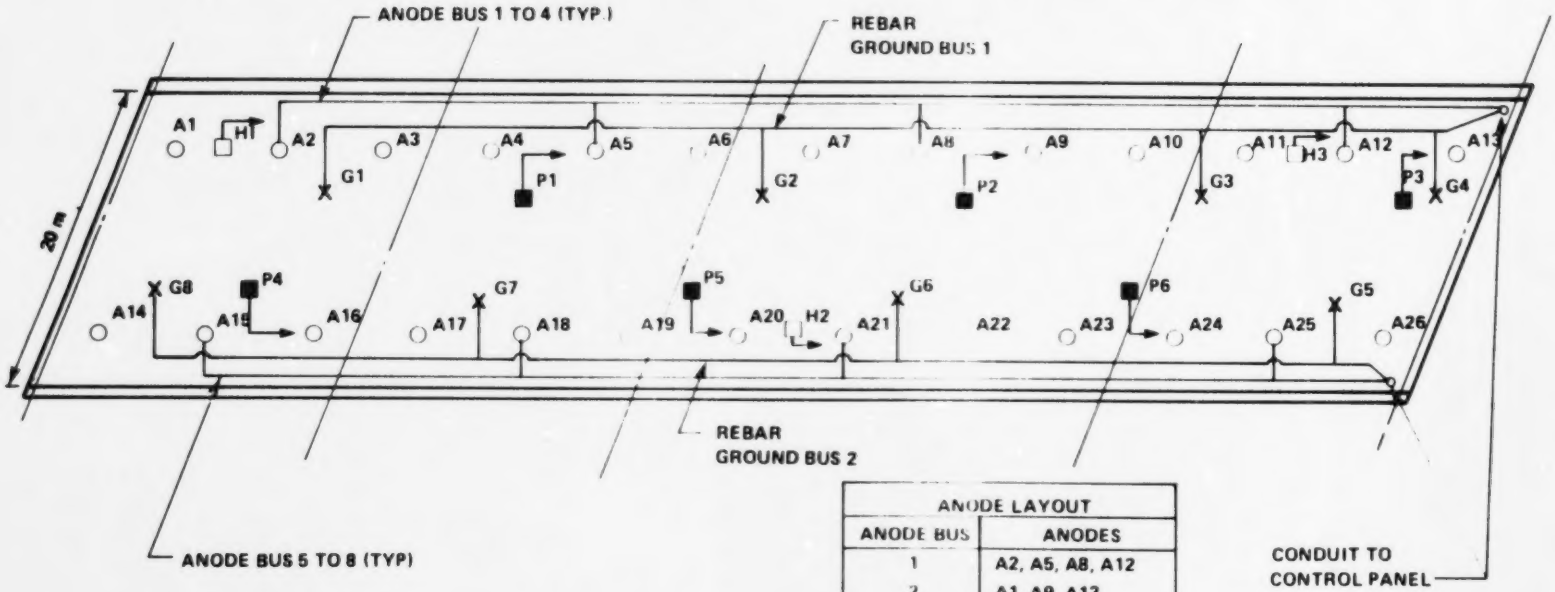


Figure 2/ Cathodic Protection Circuit – Schematic Representation of a Bridge Deck



ANODE LAYOUT	
ANODE BUS	ANODES
1	A2, A5, A8, A12
2	A1, A9, A13
3	A3, A7, A11
4	A4, A6, A10
5	A15, A18, A21, A25
6	A14, A22, A26
7	A16, A20, A24
8	A17, A19, A23

Figure 3/ Typical Placement of Anodes, Rebar Grounds, Probes, and Half-cells on a Wide Bridge

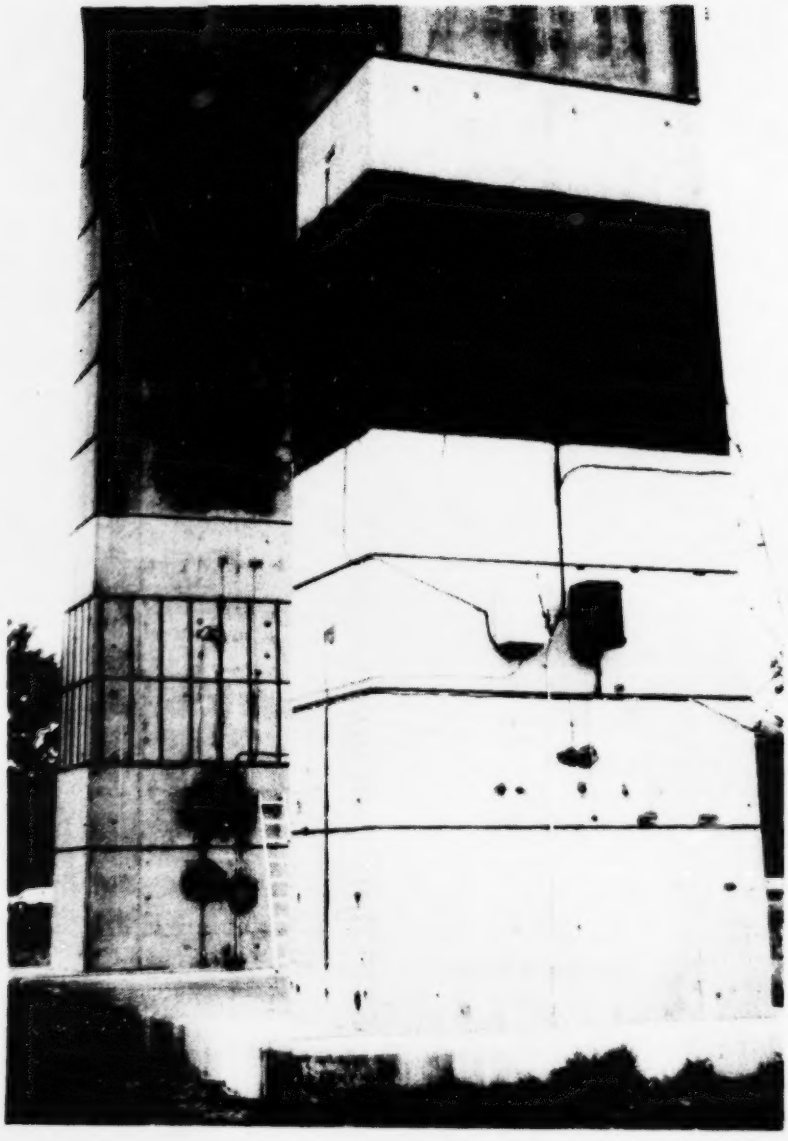


Figure 4/ Systems 1, 2, and 3 Under Construction

Figure 5/ System 5 Prior to Shotcreting

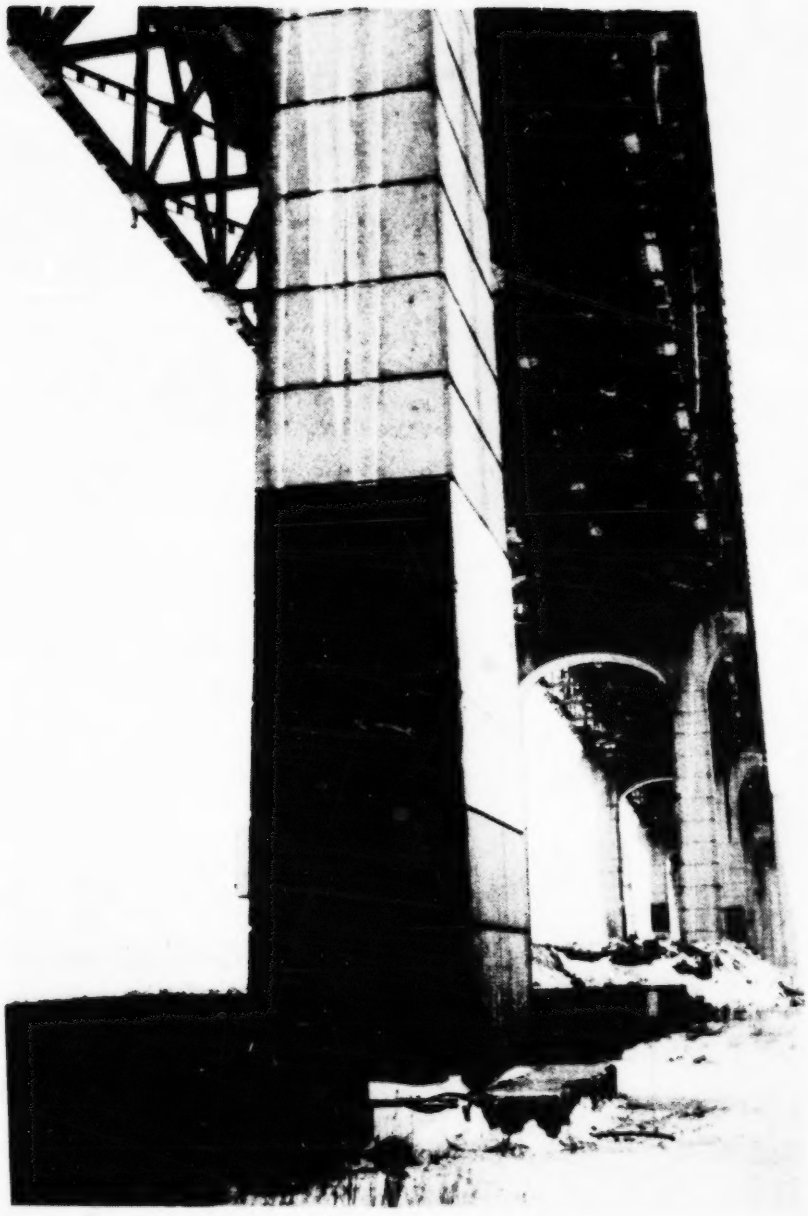


Figure 6/ System 6, North Column Face

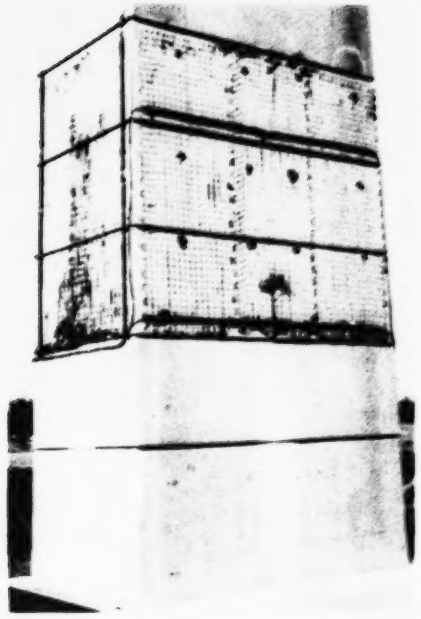


Figure7/ System 7 Prior to Shotcreting

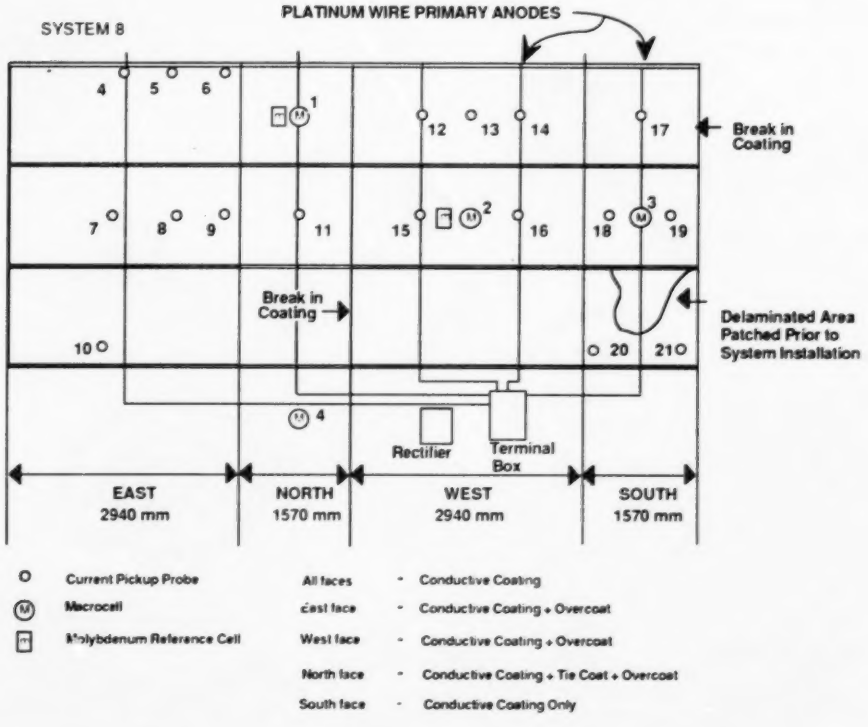


Figure 8/ Typical Anode and Instrumentation Placement, System 8

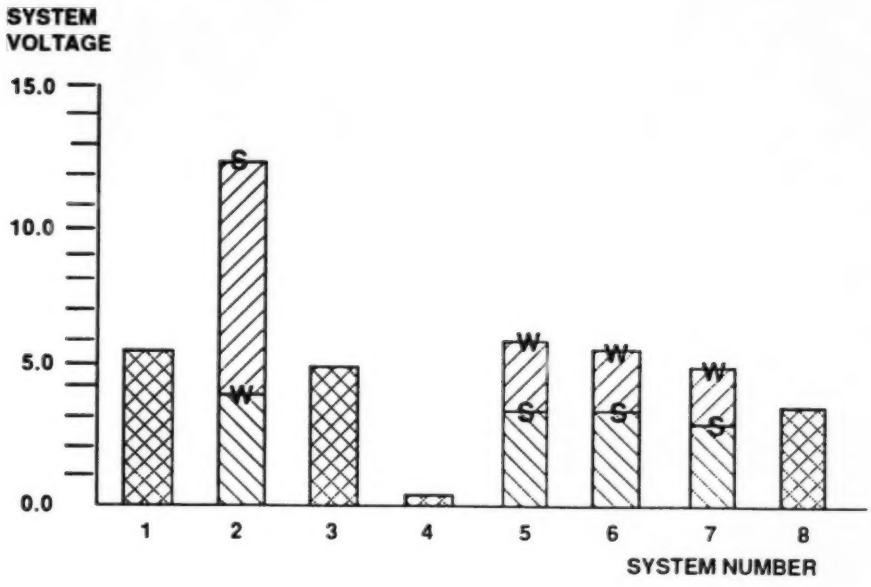


Figure 9/ Typical Operating Voltages for Burlington Systems 1 – 8

Figure 10/ Deterioration of the Conductive Paint Anode on the South Face of System 2

Figure 11/ Applications of Flame-sprayed Zinc Anode

Figure 12/ Installation of Metal Mesh Anode and Cementitious Overcoat